

On the central helium–burning variable stars of the LeoI dwarf spheroidal galaxy

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ABSTRACT

We present a study of short period, central helium–burning variable stars in the Local Group dwarf spheroidal galaxy LeoI, including 106 RR Lyrae stars and 51 Cepheids. So far, this is the largest sample of Cepheids and the largest Cepheids to RR Lyrae ratio found in such a kind of galaxy. The comparison with other Local Group dwarf spheroidals, Carina and Fornax, shows that the period distribution of RR Lyrae stars is quite similar, suggesting similar properties of the parent populations, whereas the Cepheid period distribution in LeoI peaks at longer periods ($P \sim 1.26\text{d}$ instead of $\sim 0.5\text{d}$) and spans over a broader range, from 0.5 to 1.78d. Evolutionary and pulsation predictions indicate, assuming a mean metallicity peaked within $-1.5 \lesssim [\text{Fe}/\text{H}] \lesssim -1.3$, that the current sample of LeoI Cepheids traces a unique mix of Anomalous Cepheids (blue extent of the red–clump, partially electron degenerate central helium-burning stars) and short-period classical Cepheids (blue–loop, quiescent central helium-burning stars). Current evolutionary prescriptions also indicate that the transition mass between the two different groups of stars is $M_{\text{HeF}} \sim 2.1 M_{\odot}$, and it is constant for stars metal–poorer than $[\text{Fe}/\text{H}] \sim -0.7$. Finally, we briefly outline the different implications of the current findings on the star formation history of LeoI.

Subject headings: Local Group — galaxies: individual (LeoI) — stars: variables: Cepheids

1. Introduction

Resolved stellar populations in nearby galaxies are a fundamental laboratory to constrain the impact of the environment on stellar evolution. The observables adopted to investigate these stellar systems typically rely on color-magnitude diagrams (CMDs), on kinematics or on chemical abundances. Pulsation properties of variable stars can also be adopted to provide firm constraints on the age, on the metallicity distribution of the parent stellar populations (e.g., Fornax, Feast et al. 2012), and on the star formation episodes experienced by these interesting stellar systems. This unique opportunity becomes even more important for stellar systems for which current ground-based and space telescopes do not allow us to firmly identify the main sequence turn-off stars of the different star formation episodes (e.g., CentaurusA, Rejkuba et al. 2005; M32, Fiorentino et al. 2012).

The Local Group dwarf spheroidal (dSph) galaxy LeoI plays a key role in this context. LeoI was discovered more than half century ago (Harrington & Wilson 1950) and Lee et al. (1993) suggested that its stellar content is younger than typical nearby dSphs: in particular, it is dominated by an intermediate-age population of ~ 3 Gyr. This hypothesis was soundly supported by Gallart et al. (1999), who investigated the star formation history (SFH) using deep optical CMDs reaching the oldest main sequence turn-off. Assuming $[\text{Fe}/\text{H}] = -1.7$, they found that LeoI experienced significant star formation events between approximately 7 and 1 Gyr ago. The presence in LeoI of an old stellar population (~ 10 Gyr), was demonstrated by Held et al. (2000) who first unambiguously identified a well populated horizontal branch (HB, low-mass central helium-burning stars), further confirmed by the subsequent identification of 74 candidate RR Lyrae stars (hereinafter RRLs Held et al. 2001). The same authors provided pulsation properties for 54 of them. The mean metallicity of LeoI has been estimated using the infrared Ca-triplet of red giant branch (RGB) stars. By using two independent calibrations rooted on Galactic globular clusters and on the metallicity scale provided by Carretta et al. (2009), Bosler et al. (2007) found a mean metallicity of $[\text{Fe}/\text{H}] \sim -1.34$ ($\sigma = 0.21$ dex) using 101 stars and Gullieuszik et al. (2009) found $[\text{Fe}/\text{H}] \sim -1.37$ ($\sigma = 0.18$ dex) using 50 stars. This is in quite good agreement with recent medium-resolution spectroscopy of 850 RGB stars that provided a mean metallicity of $[\text{Fe}/\text{H}] \sim -1.43$ ($\sigma = 0.33$ dex, Kirby et al. 2011). It is worth mentioning that LeoI seems to have a broad metallicity distribution, iron abundances range from ~ -2.15 to ~ -1 . A large spread in metallicity appears to be typical of several nearby dSphs. However, recent spectroscopic measurements based on high-resolution spectra indicate a significant decrease when compared with estimates based on the Ca-triplet index (Fabrizio et al. 2012).

Interestingly enough, Hodge & Wright (1978) suggested the existence of a large sample of Anomalous Cepheids (ACs) in LeoI. They identified 17 AC candidates, but the periods were estimated only for 5 of them. This finding seems partially at odds with the metal-rich chemical composition suggested by the above spectroscopic analysis, since theory and observations indicate that ACs are associated with more metal-poor stellar populations ($[\text{Fe}/\text{H}] \lesssim -1.5$). In this letter, we discuss the discovery of new RRLs and Cepheids. We focus our attention on the proper classification of the latter group by using pulsation and evolutionary models, and on its consequences on the SFH of LeoI.

2. Data samples and data reduction

This investigation is based on a large number of optical images collected from different ground-based facilities. The data reduction and calibration is part of the effort of one of us (P.B.S.) to maintain a data base of homogeneous photometry of resolved stellar clusters and galaxies. The LeoI catalog includes B , V , R , I images from 29 observing runs on 16 different telescopes during the period from 1983 January to 2002 November. A full description of the data, including the methods used to identify candidate variable stars (Welch & Stetson 1993) and to determine the pulsational properties (Stetson et al. 1998; Fiorentino et al. 2010), as well as their light curves, will be presented in a forthcoming paper. Fig.1 presents a $(V, B - V)$ color-magnitude diagram (CMD) containing 8588 stars located within a box of ~ 40 square arcmin centered on LeoI. The entire sample spans from the tip of the RGB ($V \sim 19.5$ mag) down to ~ 0.5 mag below the old main sequence turn-off. Here, we show a zoom on the HB, populated by old stars (> 10 Gyr) and the red clump (RC), typical of intermediate-age stars. Note that the RC extends to brighter magnitudes and bluer colors, typical of not-so-metal-rich environments ($[\text{Fe}/\text{H}] \leq -1.3$). The strong intermediate-age population (Gallart et al. 1999) is also evident in the blue plume of stars that reaches the magnitude level of the HB.

3. Analysis of variable stars

We have identified 157 strong candidate variable stars, and they are plotted in Fig.1. The number of phase points per object ranges from 20 (B) to more than 100 (V). We estimated accurate periods and mean magnitudes for 138 variable stars.

Two groups of variable stars with similar colors, $0.2 < B - V < 0.5$ mag, can be easily identified: a fainter one distributed along the HB ($V \sim 22.5$ mag) characterized by old, low-mass stars burning helium in an electron-degenerate core (circles) and a second one that is 1.5–2.5 mag

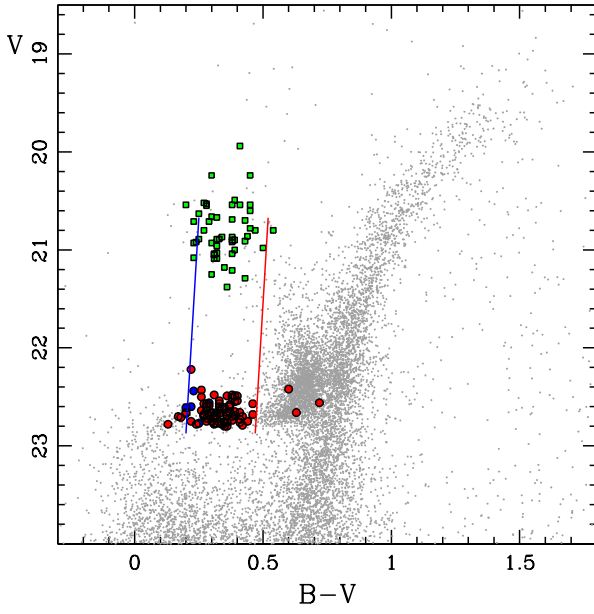


Fig. 1.— The V , $B-V$ Color-Magnitude diagram of LeoI. Red and blue circles display fundamental and first overtone RRLs. Very red variables ($B-V > 0.5$ mag) are very likely blends having the amplitude in B smaller than in V band. Squares mark Cepheids. The solid vertical lines display the predicted instability strip for RRLs and Cepheids (Fiorentino et al. 2006).

brighter (squares). The instability strip (IS) predicted by pulsation models (see vertical lines in Fig.1, Fiorentino et al. 2006) agrees quite well with both groups of variable stars. The former group (87 stars), according to their magnitude and color distributions can be safely identified as RRLs. The physical characterization of the latter group (51 stars) is less trivial, since this is a degenerate region of the CMD.

In this magnitude range, intermediate-mass ($\gtrsim 1.5 M_{\odot}$) stars burn helium in the core either in partially electron-degenerate conditions or quiescently. The latter group evolves along the so-called blue loop phase and in crossing the IS gives the classical Cepheids (CCs), while the former one evolves off the bright extent of RC stars and in crossing the IS gives the ACs. In passing, we note that also old, low-mass population II Cepheids (P2C) can occupy the same region in the CMD. However, their pulsation properties allow us to disentangle them from intermediate-mass stars (P2C are characterized, at fixed luminosity, by longer periods, see also Monelli et al. 2012; Fiorentino & Monelli 2012).

3.1. Period distribution

The period distributions of RRLs and Cepheids in LeoI are shown in Fig.2, panels *a*) and *d*) respectively. The period distribution of LeoI RRLs shows a clear separation between the 77 fundamental mode (RR_{ab}) and the nine first-overtone (RR_c) variables. The mean period of RRLs is an important parameter, since globular clusters hosting a sizable sample of RRLs show the so-called Oosterhoff dichotomy (Oosterhoff type I [OoI], $\langle P_{ab} \rangle \sim 0.55$ d; Oosterhoff type II [OoII], $\langle P_{ab} \rangle \sim 0.64$ d). The mean period showed by RR_{ab} variables in LeoI is $\langle P_{ab} \rangle = 0.59 \pm 0.05$ d. The inclusion of RR_c variables minimally affects the mean period, and indeed once we fundamentalize their periods we find $\langle P \rangle = 0.58 \pm 0.06$ d. This suggests that LeoI is an Oosterhoff intermediate system, supporting previous results (Held et al. 2001). The Oosterhoff dichotomy also shows up in the ratio between RR_c and the total number of RRLs: OoI clusters show a ratio ~ 0.2 , while for OoII clusters this is equal to ~ 0.5 . Aware that low-amplitude stars may suffer for lower completeness than high-amplitude stars, for LeoI we found $N_c/(N_c + N_{ab}) \sim 0.10$, thus suggesting that it might be more similar to an OoI cluster. These two features are in common with other nearby stellar systems (see Fig. 2 in Bono et al. 2003) and further support the impact of the environment on pulsation properties of RRLs (Monelli et al. 2012). The period distribution of LeoI Cepheids covers a broad range ($-0.3 \leq \log P \leq 0.5$) with a wide peak at $\log P \sim 0.1$. This is a period range that is poorly sampled in short-period variables due to the one-day alias. However, the very long time interval and the high number of phase points adopted in the current analysis allowed us to overcome this thorny problem. The histograms plotted in panel *d*) disclose the relevant improvement in the current sample of ACs when compared with the 17 previously identified ACs (only 5 with accurate periods;

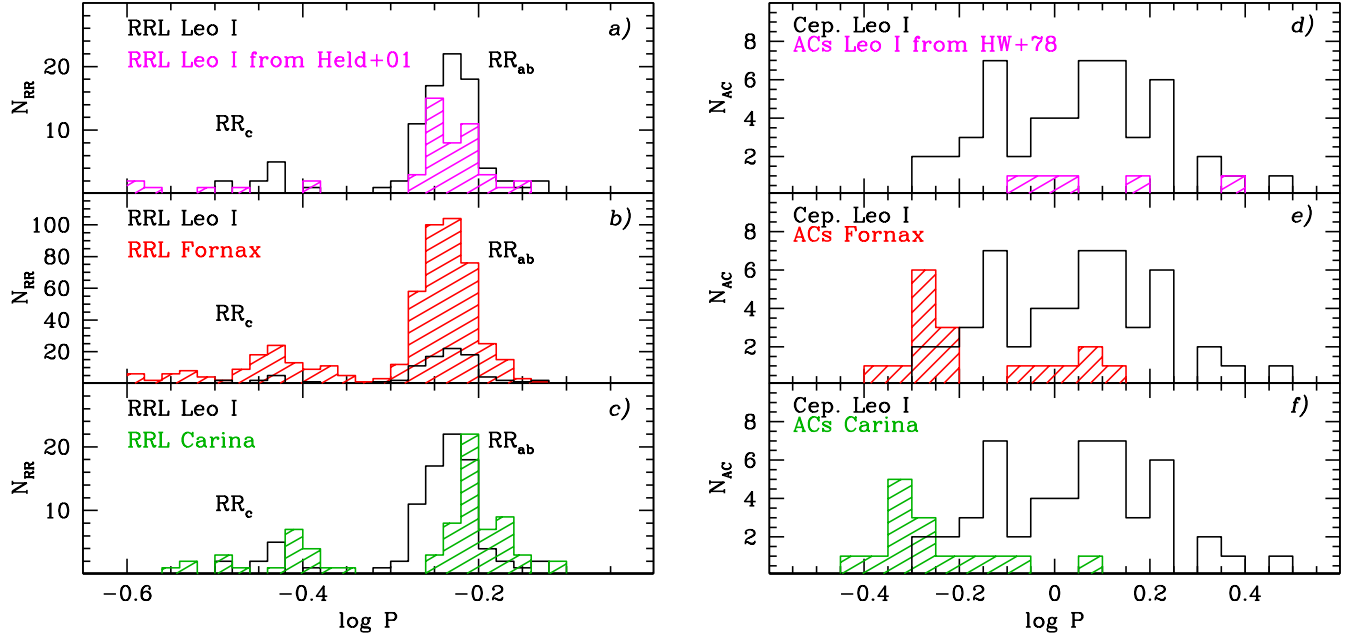


Fig. 2.— Left – period distribution of the RRL sample (90) identified in LeoI. The top panel shows the comparison with the period distribution of LeoI RRLs identified by Held et al. (54 out of 74 with well defined periods, 2001), while the middle and the bottom panels display the comparison with RRLs in Fornax (515, Bersier & Wood 2002) and in Carina (77, Dall’Ora et al. 2003), respectively. Right – same as the left panels, but for ACs. From top to bottom the panels show the comparison between the period distribution of the current sample of 51 LeoI Cepheids with the 5 bona-fide ACs identified by Hodge & Wright (1978) and with the ACs identified in Fornax (17, Bersier & Wood 2002) and in Carina (15, Dall’Ora et al. 2003).

Hodge & Wright 1978). To further constrain the pulsation properties of RRLs and Cepheids in LeoI, we adopted two empirical calibrators, namely Carina and Fornax. We selected these dSphs because they are nearby and they host sizable samples of both RRLs and ACs.

The variable star population of the Carina dSph is well understood. The 52 fundamental mode RRLs are peaked around $P=0.631$ d (see Fig.2, panel *c*), resembling an OoII system (Dall’Ora et al. 2003) and are representative of the oldest population (~ 12 Gyr). On the other hand, Carina appears to be an OoI system according to $N_c/(N_c+N_{ab})\sim 0.20$. This evidence suggests that the pulsation properties of RRLs in LeoI and in Carina are relatively similar. Carina also hosts a genuine population of 15 ACs (see Fig.2, panel *f*); Dall’Ora et al. 2003), which is fully in agreement with the observed intermediate-age stellar population (~ 600 Myr; Monelli et al. 2003) and with a spectroscopic mean metallicity peaked around $[Fe/H]=-1.80$ ($\sigma=0.24$ dex, Fabrizio et al. 2012). The period distribution of Carina ACs peaks at periods that are systematically shorter than LeoI Cepheids. This indicates that the latter group might be the progeny of a different stellar population.

We still lack a complete census of evolved variable stars in Fornax. However, Bersier & Wood (2002) reported a large number of RRLs (more than 500) suggesting a major star formation episode occurred at early epochs. The peak of RR_{ab} periods is typical of an Oo intermediate, $\langle P_{ab} \rangle = 0.585$. According to the fraction of RR_c stars, $N_c/(N_c+N_{ab})\sim 0.23$, Fornax resembles an OoI group. These findings and the histograms plotted in the panel *b*) of Fig.2 disclose that RRLs in Fornax and in LeoI also have similar pulsation properties. Bersier & Wood (2002) also detected 17 ACs showing a bi-modal period distribution, see panel *e*) of Fig.2. The short period peak is similar to the Carina peak, while the long period one is similar to the LeoI peak. No firm conclusion can be reached concerning the difference between ACs in Fornax and Cepheids in LeoI. Indeed, the small number of Fornax ACs in the long period peak might be the consequence of both a poor sampling and of the one-day aliasing.

The above empirical evidence indicates that the RRLs in Carina, Fornax and LeoI display similar pulsation properties, thus suggesting that they are the progeny of homogeneous old stellar populations. On the other hand, the current findings seem to suggest that a fraction of LeoI Cepheids could have different progenitors when compared with ACs in Carina and probably in Fornax. This could be related to the different SFHs of the dSphs under study, or simply, to observational biases that may hide a more conspicuous presence of Cepheids in such stellar systems. Only more complete studies, as the one presented here, will shed light on the reasons of such huge difference in the Cepheid sample size of LeoI when compared with other dSphs.

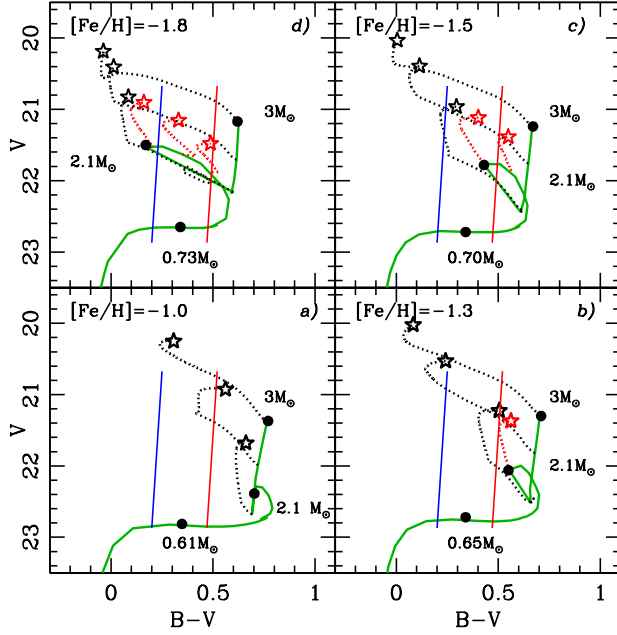


Fig. 3.— Theoretical prediction for central helium-burning structures, based on scaled-solar evolutionary models from the BaSTI database (Pietrinferni et al. 2004), for the labeled values of metallicity with a fixed $\Delta Y/\Delta Z = 1.4$ and a primordial Helium $Y = 0.23$. We assumed $\mu_0 = 22.11$ mag and $E(B-V) = 0.02$ mag. Blue and red solid lines represents the theoretical IS, as in Fig.1. Green solid lines display the Zero Age helium-burning loci for stars with masses from ~ 0.5 to $3 M_\odot$. Red and black dotted lines show evolutionary tracks during partially electron degenerate or quiescent central helium-burning, respectively. The corresponding red and black stars mark the approach to central helium exhaustion (10% of the initial abundance). Black dotted lines are for a 2.2, 2.6 and $3.0 M_\odot$. Red dotted lines are different for $[\text{Fe}/\text{H}] = -1.8$ (2.1, 1.9, $1.7 M_\odot$), $[\text{Fe}/\text{H}] = -1.5$ (2.1, $1.9 M_\odot$), $[\text{Fe}/\text{H}] = -1.3$ ($2.1 M_\odot$). At each fixed chemical composition, the three black filled circles mark the stellar mass typical of RRLs (faintest point), the transition mass (M_{HeF}) between electron degenerate and quiescent central helium-burning (middle) and the highest adopted stellar mass (brightest).

4. Discussion and final remarks

The 51 Cepheids detected in LeoI cover more than one visual magnitude in luminosity (see Fig.1) and a broad range in periods ($\sim -0.3 < \text{Log } P < 0.5$, see Fig.2). This luminosity and color range ($M_V \lesssim -0.8$ mag and $0.2 \lesssim B-V \lesssim 0.5$) is poorly investigated, because it can only be observed in metal-poor environments that experienced recent episodes of star formation. Precisely, only stars with $[\text{Fe}/\text{H}] \lesssim -1.3$ and masses around the transition mass value M_{HeF} ($\sim 2.1 M_\odot$) populate this region of the CMD. We recall that M_{HeF} is defined as the transition mass between star that ignite helium in the center under partial degenerate condition (smaller masses) or in a quiescent way (larger masses). The transition mass value is independent on the metallicity for $[\text{Fe}/\text{H}] \leq -0.7$. Since the pulsation properties of the corresponding pulsators (ACs or CCs) are very similar (Caputo et al. 2004), to properly identify the nature of our sample, a detailed comparison between evolutionary models and observations is required. The panels in Fig.3 show scaled-solar evolutionary prescriptions for central helium-burning phase for masses from ~ 0.5 to $3 M_\odot$ covering a broad range of chemical compositions (see labeled values).

A glance at the evolutionary and pulsation predictions plotted in these panels reveals the strong sensitivity of intermediate-mass stars to the chemical composition. In particular, we note that the central helium burning loci of structures with mass equal to the transition mass M_{HeF} (black dots in Fig.3) become redder and fainter for increasing metallicity. This mass value falls in the IS for a metallicity $[\text{Fe}/\text{H}] = -1.5$. In the following a detailed description of each panel:

–**Panel a)**: $[\text{Fe}/\text{H}] \sim -1$ is the maximum metallicity that allows stars entering the IS in the observed luminosity range. Only CCs with $M \geq 2.6 M_\odot$ are expected because smaller masses during their central helium-burning attain colors that are systematically redder than the IS, see Fig.3.

–**Panel b)**: A decrease in metallicity of 0.3 dex slightly affects the evolutionary scenario, stars burning helium in partially electron degenerate core do not (or slightly) cross the IS during their evolution. The minimum mass value of quiescent central helium-burning structures crossing the IS decreases to $2.2 M_\odot$, larger than M_{HeF} . This means that the system still produces mostly CCs, but with periods shorter than in the previous case.

–**Panel c)**: A further decrease in the metallicity of 0.2 dex causes a dramatic change in the evolutionary scenario, and indeed the M_{HeF} evolutionary model falls inside the IS, within a magnitude range of $V \sim 21$ – 22 mag. Thus, this region is almost entirely populated by ACs, while the brighter portion contains some CCs.

–**Panel d)**: The change in the evolutionary scenario outlined for $[\text{Fe}/\text{H}] = -1.5$ becomes even more pronounced for $[\text{Fe}/\text{H}] = -1.8$. The further decrease in metallicity implies that a significant portion of the hook performed by the central helium burning loci for stellar masses less than M_{HeF} falls in-

side the IS. This means that more metal–poor systems are expected to produce a significant number of ACs. Note that in this metal–poor scenario ($[\text{Fe}/\text{H}] \lesssim -1.5$) the occurrence of quiescent central helium-burning structures would be traced not only by short-period CCs, but also by Blue Tip stars, located at colors systematically bluer than Cepheids and marking the maximum extent in color of the blue loop where stars spend most of their central helium-burning time ($20 \lesssim V \lesssim 21$, $B-V \sim 0$).

When we compare our observations with these theoretical prescriptions (see Fig.4), we find that they agree quite well with the two intermediate chemical compositions, namely $[\text{Fe}/\text{H}] \sim -1.5$ (top) and $[\text{Fe}/\text{H}] \sim -1.3$ (bottom). Indeed, current theoretical predictions for the central helium burning loci account for both low- (HB) and intermediate-mass (RC) helium-burning stars. In the following we outline the properties of LeoI Cepheids at fixed metallicity in the current evolutionary scenario. If we assume that the mean metallicity of LeoI peaks at $[\text{Fe}/\text{H}] \sim -1.3$ then the bulk of the LeoI Cepheids is made by short period CCs, with masses systematically larger than M_{HeF} and an age of their progenitors younger than 650 Myr. On the other hand, if we assume $[\text{Fe}/\text{H}] \sim -1.5$ then part of the LeoI Cepheids is made by ACs, with a typical star mass populating the IS equal to M_{HeF} . The interesting feature disclosed by the top panel of Fig.4 is that the bright tail of LeoI Cepheids seems to consist of CCs (quiescent central helium-burning) while the fainter tail seems to consist of ACs (partial electron degeneracy central helium-burning). This means that the stellar mass distribution of LeoI Cepheids should be larger and range from $2M_{\odot}$ (700 Myr) to $\sim 3M_{\odot}$ (250 Myr).

Note that the above discussion is based on the assumption that the bulk of the bright variable stars is characterized by one mean metallicity. However, spectroscopic ($[\text{Fe}/\text{H}] \sim -1.43 \pm 0.33$; Kirby et al. 2011) and photometric indicators (width in color of the RGB) support the evidence that stellar populations in LeoI are characterized by a spread in metallicity, thus suggesting that they might be a unique mix of both ACs and CCs.

The present variability study provides new constraints on the star formation history of LeoI. From a qualitative point of view, the existence of 106 RRLs, along with a well defined HB, tells us about a very old event of star formation experienced by the galaxy more than 10 Gyr ago. Moreover, the detection of a large sample of Cepheids, 51, suggests that an intermediate-age episode of star formation also occurred, accordingly with a very well defined RC feature. Finally, the number of detected objects tell us that these two events of star formation involved a considerable amount of gas.

However, our knowledge of variable stars can drive more quantitative conclusions. Our sample of Cepheids occupy a very intriguing and poorly investigated luminosity and color range, $M_V \lesssim -0.8$ mag and $0.2 \lesssim B-V \lesssim 0.5$. Few Cepheids that occupy this region of the CMD are observed in other dSph galaxies. On the contrary, many of them are observed in irregular

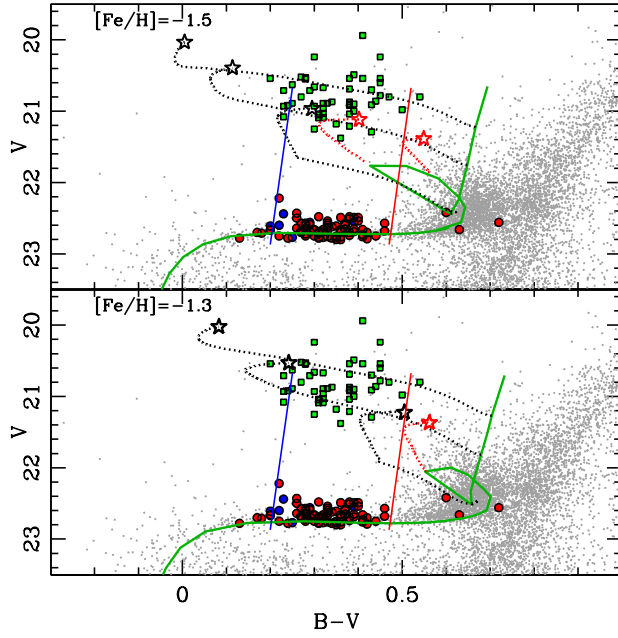


Fig. 4.— Same as in Fig.3, but for two metal–intermediate chemical compositions namely $[\text{Fe}/\text{H}] = -1.5$ (top) and $[\text{Fe}/\text{H}] = -1.3$ (bottom). Symbols and colors used of the observed variables as in Fig.1.

dwarfs like LeoA (Dolphin et al. 2002), SextansA and B (Sandage & Carlson 1985; Piotto et al. 1994; Dolphin et al. 2003), and Phoenix (Gallart et al. 2004). Using current scaled-solar theoretical prescriptions, we have shown that a very narrow range in stellar masses (around the transition mass, M_{HeF}) and metallicity ($-1.5 \lesssim [Fe/H] \lesssim -1.3$) account for LeoI Cepheid properties. The mean metallicity agrees quite well with recent spectroscopic measurements. Moreover, the quoted scenario accounts for the difference in the Cepheid period distribution (peaked at 1.26d instead of 0.5d) observed in LeoI when compared with Carina and Fornax dSphs. For these galaxies, we are carrying out extensive, archival-based variability studies in order to identify the reasons of the huge difference in their Cepheid sample.

The current scenario depends on the adopted theoretical assumptions. In a forthcoming paper we plan to investigate the dependency on alpha-enhancement, helium content and mass loss since these inputs affect the luminosity and colors of central helium burning phases (Castellani et al. 2000; Girardi & Salaris 2001; Salaris & Girardi 2002).

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